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**IN THE UNITED STATES PATENT AND TRADEMARK OFFICE**

**PATENT APPLICATION**

**Joseph Earl FORD, David Thomas NEILSON**

**CASE:** **Ford 46-6**

**TITLE:** **Method and Apparatus for Spatial-Shift Wavelength Multiplexing in Communication Systems**

**Assistant Commissioner for Patents**
**Washington, D.C. 20231**
**Box Patent Application**



**SIR:**

Enclosed are the following papers relating to the above-named application for patent:

- Transmittal letter **(2x)** with deposit account authorization
- Title Page, Specification, Claims 1 to 13 & Abstract (17 pages)
- Unexecuted Declaration and Power of Attorney (4 p.)
- Three (3) sheets of drawings (Figs. 1 to 5)
- Return receipt postcard

| CLAIMS AS FILED | | | | |
|---|---|---|---|---|
| | NO. FILED | NO. EXTRA | RATE | CALCULATIONS |
| Total Claims | 13 - 20= | 0 | x $18= | $ |
| Independent Claims | 2 - 3= | 0 | x $78= | $ |
| Multiple Dependent Claim(s), if applicable | | | $260= | $0 |
| Basic Fee | | | | $690 |
| | | | TOTAL FEE: | $690 |

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[] Priority is claimed for this invention and application, corresponding application(s) having been filed in on , Application No. .

Respectfully,

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Attorney for Applicant(s)

Date: July 26, 2000

Attorney Docket: Ford 46-6

By Express Mail # EL350351745US

# APPLICATION FOR UNITED STATES LETTERS PATENT

# METHOD AND APPARATUS FOR SPATIAL-SHIFT WAVELENGTH MULTIPLEXING IN COMMUNICATION SYSTEMS


Inventor(s):

**Joseph Earl FORD**
**David Thomas NEILSON**

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

The present invention relates generally to methods and systems for spatial-shift, wavelength multiplexing of optical signals in an optical communication system. More specifically, the invention relates to methods and systems for routing optical signals through an optical communication system by spatially shifting the signals and dispersing the signals into discrete regions onto an optical plane.

### 2. Description of the Related Art

With the advent of high-speed wavelength division multiplexed (WDM) and dense wavelength division multiplexed (DWDM) systems over the last few years, optical routers in such systems have played an increasingly significant role for routing multi-wavelength, highly dispersible signals through the system. Wavelength multiplexers include various designs which produce different kinds of output signals for particular applications. Generally speaking, the desired passband response of a WDM router is a flat, uniform response over a pre-determined wavelength range surrounded by sharp drop-offs for out-of-band signals. Figure 1 illustrates the preferred or optimal passband response of a WDM or DWDM wavelength filter as a function of the transmissivity of the filter. As can be seen in Figure 1, the response is flat at about 0dB centered about a center wavelength $\lambda_0$. Moreover,

the response has a sharp transition region 10 which tends to ensure that good signal transmission is achieved with little loss in the signal.

The fundamental problem associated with most diffraction grating routers is that imaging through a diffraction grating creates a linear shift of the focal spot as a function of wavelength, a result which is in conflict with the goal of achieving a segmented, flat-topped passband that is inherently a non-linear function. For example, a collimated beam can illuminate a sequence of dielectric notch filters so that each reflects one wavelength range. This arrangement can produce a flat passband, but since the insertion loss scales linearly with the number of wavelength channels, it is not generally regarded as suitable for large channel count WDM or DWDM systems. Array waveguide routers (AWR), sometimes referred to as "Dragone" routers, can provide large channel counts of eighty or more but tend to produce Gaussian shaped passbands that do not have sharp transition points and are therefore quite lossy.

Free-space optical wavelength routers have been manufactured using a combination of lenses, gratings and fiber or waveguide input/output elements. However, these types of routers include waveguides that have a small width core relative to the waveguide cladding layer and a minimum pitch between guiding channels on a fiber array or multi-waveguide substrate. The lateral alignment tolerance necessary to couple with less than about ten percent loss is typically one to three microns, whereas the pitch between adjacent output waveguides is from twenty to two hundred and fifty microns. This tends to create a narrow passband shape with a broad "dead" region between center wavelengths, which is highly disadvantageous for WDM and DWDM systems. To alleviate this problem, a combination of optical defocus elements, mode-expanding waveguide shapes, and closely spaced output

channels can flatten the passband and reduce the dead space; however, these techniques also tend to create excess loss and reduce optical throughput efficiency.

There accordingly exists a long-felt but unresolved need in the art for methods and systems for imaging with optical routers in a communication system which produces a segmented, flat-topped passband. It would be desirable if such methods and systems took advantage of the linear dependent wavelength shift associated with spatial-shift wavelength elements in which wavelength and imaging dispersion determines a region to illuminate with an optical spectrum. It would further be desirable if the spatial shift in the spectrum were defined simply by the surface geometry of the element since this will produce a clean spatial shift with little to no loss of signal. Such needs have not heretofore been met or fulfilled in the art.

## SUMMARY OF THE INVENTION

The aforementioned long-felt needs are met, and problems solved, by optical routers and methods for routing optical signals through optical communication systems provided in accordance with the present invention. The inventive methods and systems provide a spatially-shifted and multiplexed signal by first linearly dispersing a spectrum comprising a plurality of wavelengths to create a plurality of discrete regions of signal on an intermediate image plane. The linearly dispersed regions are then spatially disbursed and the discrete regions are re-imaged to remove the dispersion associated with linearly dispersing the spectrum.

The optical routers and methods provided in accordance with the invention thus achieve efficient spatial shifting of wavelengths to multiplex signals traversing the communication system. By first linearly dispersing the region into discrete regions and then spatially shifting the regions, a flat passband with sharp transition regions as a function of wavelength can be realized. Moreover, through the use of simple optical elements, optical routers claimed and described herein are economical and easy to fabricate. Such results have not heretofore been achieved in the art.

Other objects and features of the present invention will become apparent from the following detailed description considered in conjunction with the accompanying drawings. It is to be understood, however, that the drawings are designed solely for purposes of illustration and not as a definition of the limits of the invention, for which reference should be made to the appended claims. It should be further understood that the drawings are not

necessarily drawn to scale and that, unless otherwise indicated, they are merely intended to conceptually illustrate the structures and procedures described herein.

## BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings wherein like reference numerals denote similar elements throughout the views:

Figure 1 is a graph of the optimal passband region which is achieved by the methods and apparatus of the present invention;

Figure 2 is a conceptual diagram of an optical router of the present invention which linearly disperses and then spatially shifts an optical spectrum to achieve the desired optimal passband depicted in Figure 1;

Figure 3 is a diagrammatic view of a preferred embodiment of the inventive optical router utilizing a lens and grating to produce the desired passband of Figure 1;

Figure 4 is a diagrammatic view of another preferred embodiment of the inventive optical router utilizing a concave mirror; and

Figure 5 is an elevated prospective view of micro-electromechanical structure (MEMS) optical router of the present invention.

Figure 5 is an elevated prospective view of micro-electromechanical structure (MEMS) optical router of the present invention.

**DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS**

Referring now to the drawings, Figure 2 shows conceptually the various stages that a spectrum of light undergoes in accordance with the present invention to produce a spatially-shifted, multiplexed spectrum with an optimum passband depicted generally in Figure 1, which is a non-linear response. An input source 20 transmits a spectrum containing a plurality of signals. In Figure 2, the spectrum is shown by way of example as including eight discrete wavelengths, although it will be recognized by those skilled in the art that any number of discrete signals may be transmitted by input source 20. The spectrum is preferably transmitted by an optical fiber, but may also be transmitted by other equivalent input sources such as a lens, mirror, or other optical device adapted to carry multiplexed signals having a spectrum. The signal is imaged onto an intermediate image plane 30 wherein the individual wavelength signals are linearly dispersed into discrete regions in a substantially linear pattern 40 from the original position 50 of the multiplexed signal. As used herein, the term "linearly dispersed" means that the discrete regions are broken or separated into separate and distinct regions generally along a transverse, substantially linear line across the intermediate image plane.

In accordance with the invention, the linearly dispersed region on image plane 30 is then spatially, laterally shifted by a discontinuous optical element. The discontinuous optical element used to accomplish this result will preferably comprise a set of independent, micro-optic pathways having substantially adjacent entrance apertures and a set of output apertures that may be set by design for the particular application in which the inventive optical routers will be implemented. Any type of device that comprises such an arrangement, or equivalents thereof, are intended to be within the scope of the present invention. For example, but without intending

to limit the invention in any way, the discontinuous optical element may be a grating, interference device, spatial light modulator, lens, reflecting element, refracting element, diffracting element, planar v-groove mirror, combinations thereof, and any other type of element which can spatially shift a spectrum.

Preferably, the discontinuous element is placed proximate the intermediate image plane and, as can be seen in Figure 2, shifts the discrete regions above or below the linear dispersed pattern 40 into a plurality of spatially shifted positions 60 depending on the construction of the discontinuous optical element and as desired for the particular application in which the inventive optical router will be used. A re-imaging optical element is then employed to remove the linear dispersion introduced by the linear dispersion element so that those regions which share a common spatial position are superimposed on one another, as at 70, 80, 90 and 100 in Figure 2, to produce the spatially shifted, multiplexed spectrum shown at 110 which has a flat passband with sharp transition points substantially as shown in Figure 1.

Figure 3 depicts a preferred embodiment of an optical router of the present invention in which the linear dispersion element is a micro-optic input array 120 comprising a plurality of input fibers 130, each carrying a discrete wavelength. The intermediate image plane 30 is projected by a focussing lens 140 onto a grating 150 which acts as the discontinuous optical element of the optical router of Figure 3. Grating 150 is preferably a planar silicon wafer having a series of v-grooves fabricated thereon which, when illuminated by the spectrally dispersed lines focussed on it by lens 140, can laterally shift the regions formed by micro-optic array 120. When the dispersed spectrum falls onto grating 150, it is reflected back through lens 140 which focuses the laterally shifted spectrum onto an output waveguide 160, thereby removing the initial

linear dispersion created by the input array 120 in the first instance. This produces the flat passband response depicted in Figure 1.

While the embodiment of the inventive optical router shown in Figure 3 effectively produces a spatially-shifted, multiplexed signal with a flat passband, it tends to be rather bulky in that it occupies a relatively large amount of real estate in the optical communication system. Referring now to Figure 4, the depicted alternative embodiment of the inventive optical router advantageously reduces the physical size of the router of Figure 3 by about half by employing a concave mirror 170 as the re-imaging element and a multiple wavelength laser array 180 as the linear input dispersion element. In accordance with the optical router embodiment of Figure 4, laser array 180 projects a linearly dispersed spectrum onto an intermediate image plane on which is placed a grating 190 that acts as the discontinuous optical element to spatially shift the regions.

Preferably, a series of shift mirrors 200 pickup the individual regions which have been linearly dispersed by grating 190 and reflect them to concave mirror 170. Mirror 170 reflects the linearly and spatially shifted spectrum back onto the grating 190 and the grating, re-images the spectrum to remove the linear dispersion and focus the spectrum on output fiber 210.

This similarly produces a spatially shifted, flat passband output signal. Moreover, by using a concave mirror 170 to focus the spatially shifted signal back through grating 190, the grating is used to both linearly disperse and redisperse the signal, thereby greatly reducing the size of the resulting optical router. Moreover, the embodiment of Figure 4 may be fabricated as a single molded part, for example as molded glass, plastic or glass filled epoxy, so that the device can accept waveguide arrays and fibers for use therein within a 3 to 15 micron tolerance, which

is today the current the standard. The optical features such as the curved, concave mirror 170, ridged diffraction grating 190 and stepped shift mirrors 200 may all be formed by the surface topography of the molded part and optionally coated with the appropriate metal or dielectric reflectors. The optical signals are therefore transmitted back and forth within the volume of the optical router of Figure 4 which is fully contained in a relatively small space.

The optical routers of the present invention may also be constructed as a MEMS (micro-elcctromechanical structure) device by fabricating the device on a silicon wafer with electromechanically actuated parts. A MEMS device of this nature will create a controllable amount of lateral shift of the spectrum, and will therefore be adjustable for use in many different types of applications. Figure 5, depicts such a MEMS optical router 220 for producing spatially-shifted, multiplexed signals in accordance with the invention is shown at 220. As is known, the illustrated MEMS device 220 is fabricated on a silicon wafer 230 and comprises a MEMS tilt mirror 240 which moves laterally 250 across the silicon substrate when actuated by electrical control lines 260. A conventional scratch drive actuator 270 controls the movement of tilt mirror 240.

Tilt mirror 240 has an initial and a final position between which it is selectively moveable (as indicated by the arrow 250) and can therefore be used as both the linear dispersion element and the re-imaging element in accordance with the invention. A tilted mirror plate 280 acts as the discontinuous optical element to provide the lateral shift described above. Although only one tilt mirror 240 and tilted mirror plate 280 are shown in Figure 5, it will be recognized by those skilled in the art that these two elements may instead comprise an array of optical elements as heretofore described to produce the desired spatially-shifted, multiplexed spectrum

of the present invention. Moreover, the optical router of Figure 5 may be used to control the wavelength passband position in a WDM or DWDM router or to switch between multiple output waveguides by virtue of the movable nature of the combination tilt mirror 240 and tilt mirror plate 280.

Thus, the disclosed optical routers for producing spatially-shifted, multiplexed signal and methods of routing optical signals in communication systems, in accordance with the present invention, provide efficient and economical routing and transmission of optical signals. The inventive routers and methods achieve an extremely flat passband with high transmission having very sharp transition points. This advantageously allows for very low loss transmission of multiple optical channels in a communication system with notably high accuracy. Such results are highly advantageous for WDM and DWDM optical communication systems and have not heretofore been effectively achieved in the art with prior optical routers and methods.

Thus, while there have shown and described and pointed out fundamental novel features of the invention as applied to a preferred embodiment thereof, it will be understood that various omissions and substitutions and changes in the form and details of the devices illustrated, and in their operation, may be made by those skilled in the art without departing from the spirit of the invention. For example, it is expressly intended that all combinations of those elements and/or method steps which perform substantially the same function in substantially the same way to achieve the same results are within the scope of the invention. Moreover, it should be recognized that structures and/or elements and/or method steps shown and/or described in connection with any disclosed form or embodiment of the invention may be

incorporated in any other disclosed or described or suggested form or embodiment as a general matter of design choice. It is the intention, therefore, to be limited only as indicated by the scope of the claims appended hereto.

## CLAIMS

What is claimed is:

1. An optical router in an optical communication system for routing multiplexed signals having a plurality of wavelengths that create a spectrum through the communication system by spatially shifting the wavelengths, said optical router including an output element comprising:

a linear element for receiving the signals having the plurality of wavelengths and for dispersing the spectrum into discrete regions onto an intermediate image plane;

a discontinuous optical element in optical communication with the intermediate image plane for laterally shifting the discrete regions by predetermined lengths to produce a laterally shifted spectrum, each of said predetermined lengths being associated with one of the discrete regions; and

a re-imaging optical element for receiving the laterally shifted spectrum and for removing the dispersion created by said linear element and for re-imaging the spectrum onto the output element.

2. The optical router of claim 1, wherein said linear element comprises a micro-optic array.

3. The optical router of claim 2, wherein said micro-optic array comprises a plurality of input fibers each is adapted to transmit one of the plurality of wavelengths.

4. The optical router of claim 1, wherein said linear element comprises a

micro-electromechanical structure tilt mirror that is electromechanically actuatable.

5. The optical router of claim 1, wherein said discontinuous optical element comprises a grating.

6. The optical router of claim 5, wherein said grating comprises a silicon wafer and a plurality of v-shaped grooves defined in the silicon wafer.

7. The optical router of claim 1, wherein said discontinuous optical element comprises a micro-electromechanical structure (MEMS) tilt mirror plate.

8. The optical router of claim 1, wherein said re-imaging optical element comprises a lens for receiving the spatially shifted spectrum and a grating for removing the dispersion and focusing the received spatially diffused spectrum onto the output element of the router.

9. The optical router of claim 1, wherein said re-imaging element comprises a concave mirror.

10. A method for routing optical signals having a plurality of wavelengths that create a spectrum through an optical communication system by spatially shifting the wavelengths, comprising the steps of:

linearly imaging the spectrum into discrete regions and onto an intermediate image plane, wherein the imaging step introduces linear dispersion into the spectrum;

laterally shifting the discrete regions by predetermined lengths to produce a

laterally shifted spectrum, each of said predetermined lengths being associated with one of the discrete regions; and

re-imaging the laterally shifted spectrum to remove the linear dispersion introduced by said imaging step and for outputting the latterly shifted spectrum onto an output element in the optical communication system.

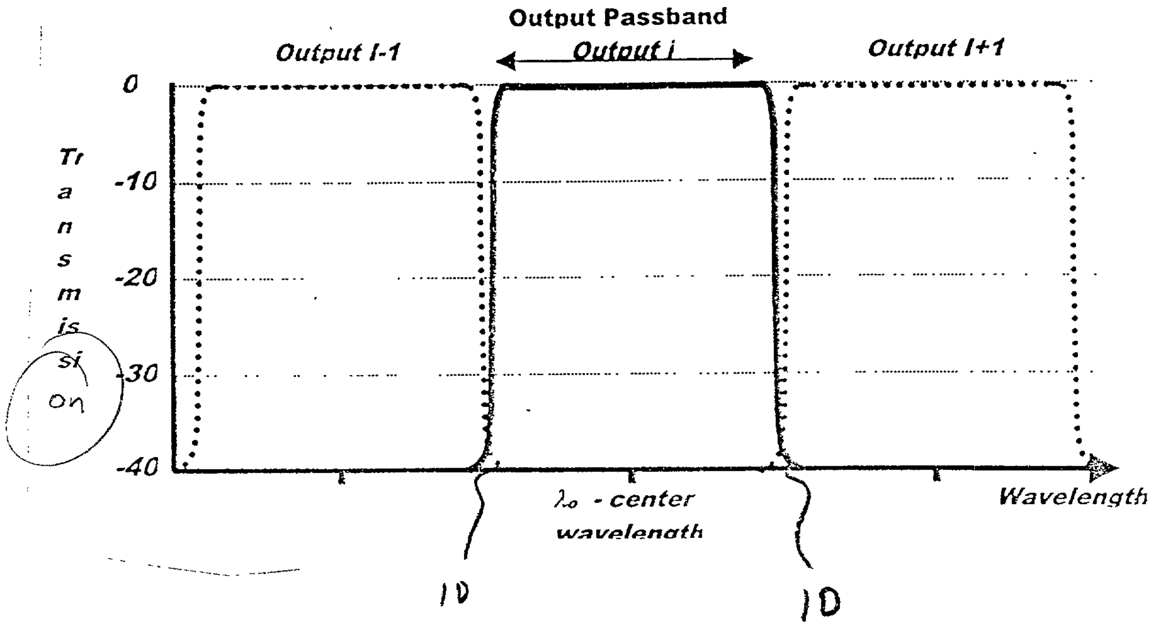
11. The method of claim 10, wherein said shifting step comprises diffracting the spectrum to introduce lateral space shifts to the discrete regions.

12. The method of claim 11, wherein said shifting step further comprises reflecting the laterally spaced shifted spectrum with an array of reflecting mirrors before re-imaging the spectrum.

13. The method of claim 10, wherein said re-imaging step further comprises reflecting the shifted, linearly dispersed spectrum through an element for removing the linear dispersion.

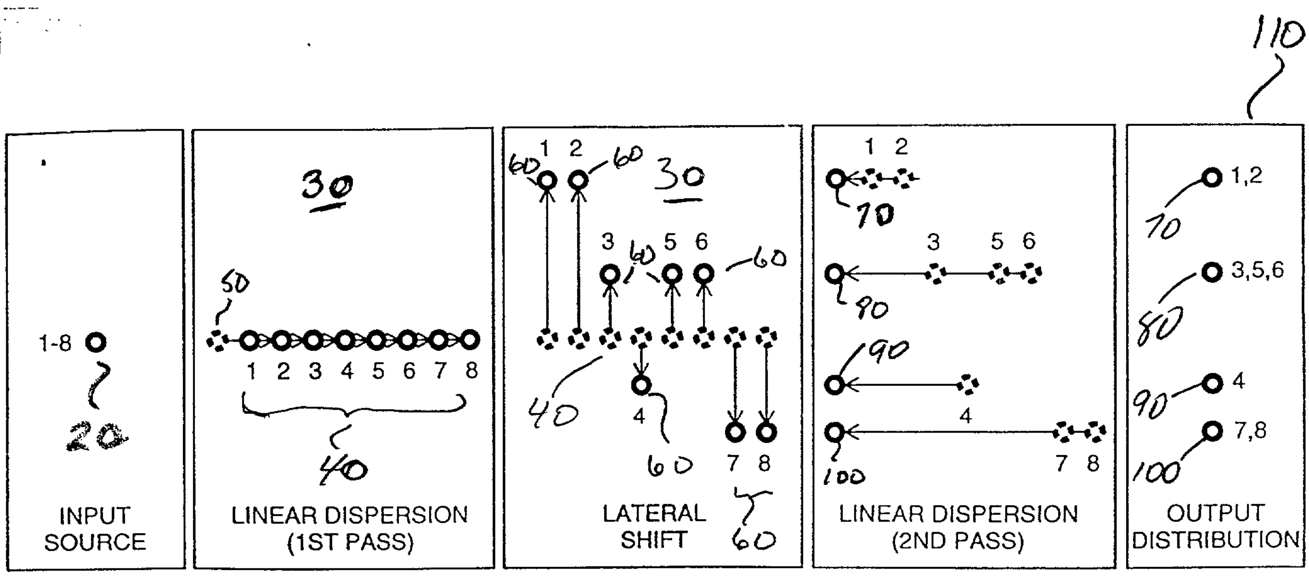
## ABSTRACT OF THE DISCLOSURE

Methods and apparatus for spatially-shifting and multiplexing optical signals for transmission in a wavelength division multiplexed or dense wavelength division multiplexed optical communication system linearly disperse the optical signals and then spatially, laterally shift the signals. The spatially shifted, dispersed signals are thereafter re-imaged to remove the linear dispersion so that the spatially shifted signals can then be transmitted through the optical communication system. The spatially-shifted, multiplexed signals have a flat passband with sharp transition points so that the transmitted signals are routed through the optical communication system with low loss and high signal integrity.



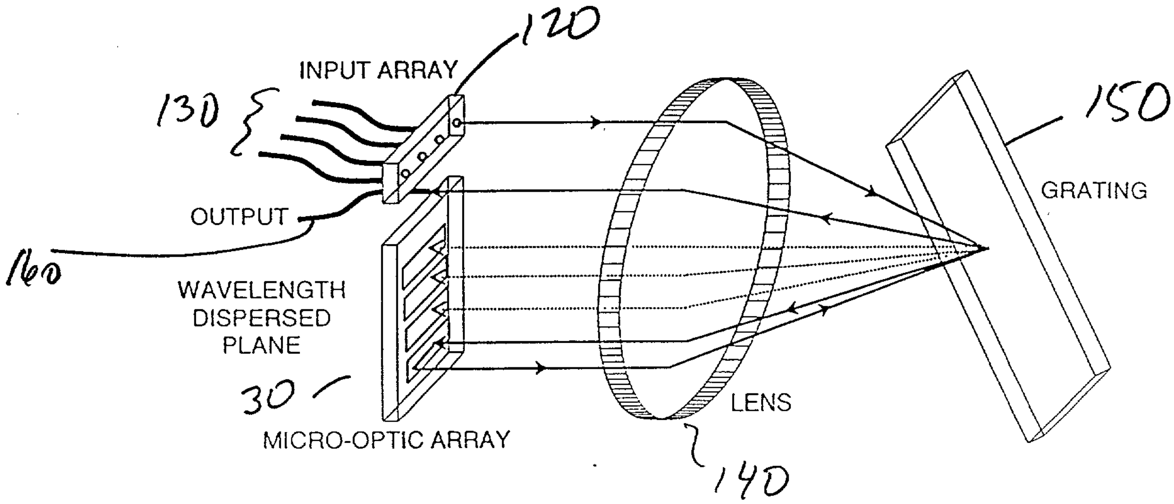
Output Passband
Output I-1
Output i
Output I+1
0
-10
-20
-30
-40
Transmission
$\lambda_o$ - center wavelength
Wavelength
10
10


Fig. 1



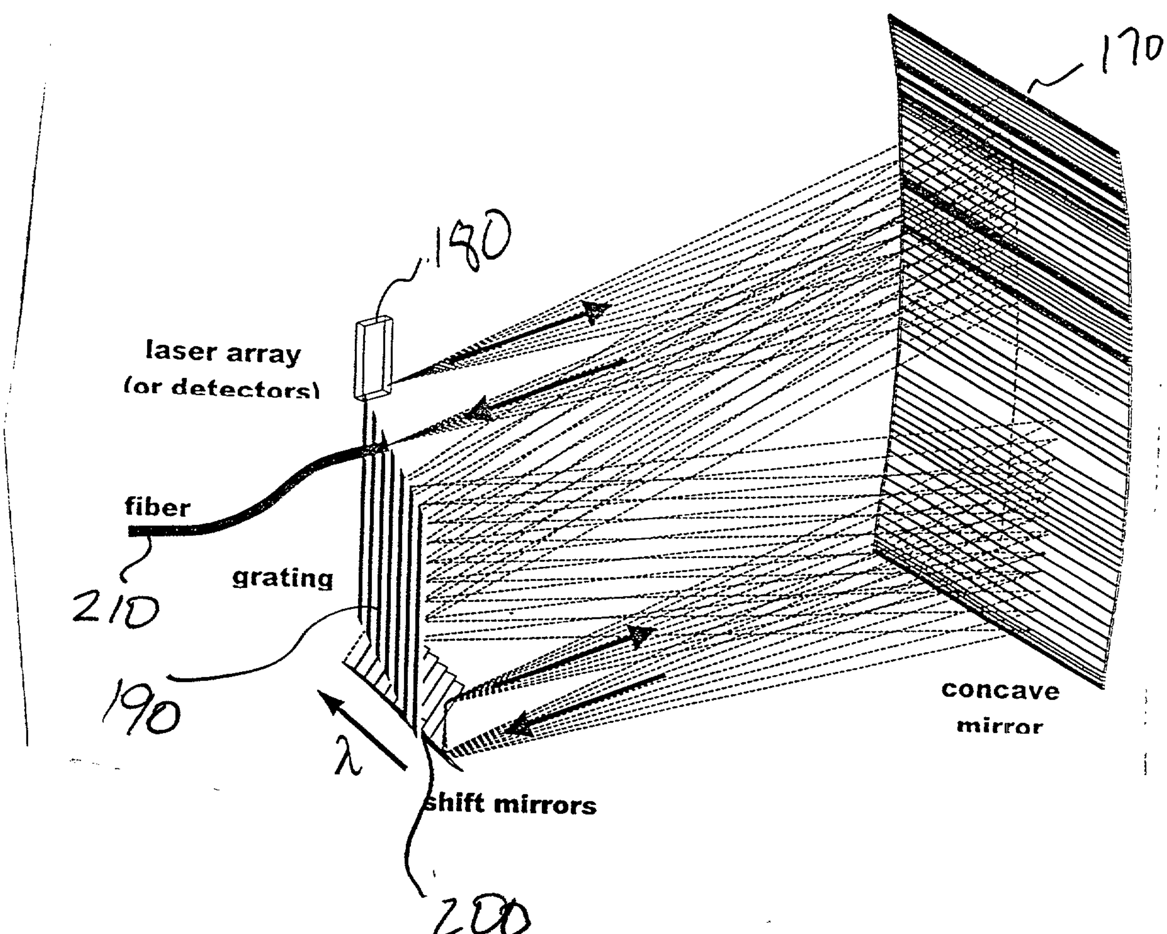
110
1-8
20
INPUT SOURCE
30
50
1 2 3 4 5 6 7 8
40
LINEAR DISPERSION (1ST PASS)
1 2
60
60
30
3 5 6
60
60
40
4
60
7 8
60
LATERAL SHIFT
1 2
70
3 5 6
90
90
4
100
7 8
LINEAR DISPERSION (2ND PASS)
1,2
70
3,5,6
80
4
90
7,8
100
OUTPUT DISTRIBUTION


Fig. 2



120
INPUT ARRAY
130
150
GRATING
OUTPUT
160
WAVELENGTH
DISPERSED
PLANE
30
MICRO-OPTIC ARRAY
LENS
140


Fig. 3



170
180
laser array
(or detectors)
fiber
210
grating
190
λ
shift mirrors
200
concave
mirror


Fig. 4

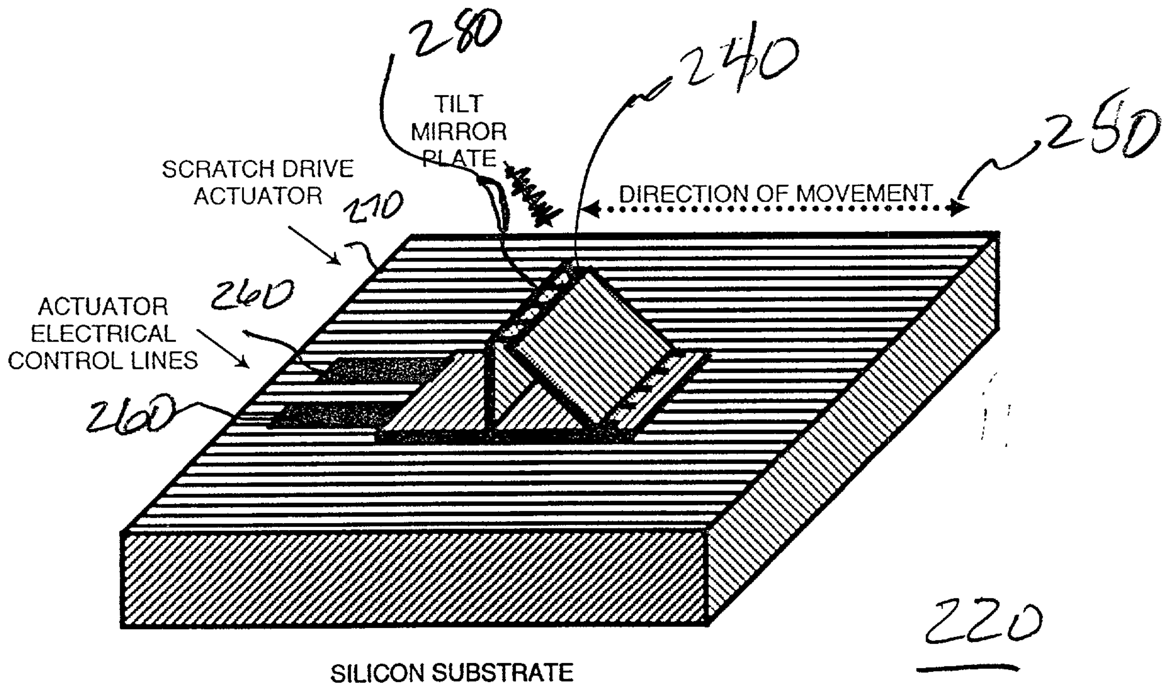

280
240
250
TILT
MIRROR
PLATE
SCRATCH DRIVE
ACTUATOR
210
DIRECTION OF MOVEMENT
260
ACTUATOR
ELECTRICAL
CONTROL LINES
260
SILICON SUBSTRATE
220

Fig.5

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Declaration and Power of Attorney

As the below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

**Method and Apparatus for Spatial-Shift Wavelength Multiplexing in Communication Systems**

the specification of which ***is attached hereto.***

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by an amendment, if any, specifically referred to in this oath or declaration.

I acknowledge the duty to disclose all information known to me which is material to patentability as defined in Title 37, Code of Federal Regulations, 1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, 119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

None

I hereby claim the benefit under Title 35, United States Code, 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, 112, I acknowledge the duty to disclose all information known to me to be material to patentability as defined in Title 37, Code of Federal Regulations, 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application:

None

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

I hereby appoint the following attorney(s) with full power of substitution and revocation, to prosecute said application, to make alterations and amendments therein, to receive the patent, and to transact all business in the Patent and Trademark Office connected therewith:

| | |
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| Eli Weiss | (Reg. No. 17765) |

I hereby appoint the attorney(s) on ATTACHMENT A as associate attorney(s) in the aforementioned application, with full power solely to prosecute said application, to make alterations and amendments therein, to receive the patent, and to transact all business in the Patent and Trademark Office connected with the prosecution of said application. No other powers are granted to such associate attorney(s) and such associate attorney(s) are specifically denied any power of substitution or revocation.

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**ATTACHMENT A**

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